Current Approach in Clinical Electron Beam Dosimetry

Dimitris Mihailidis, Ph.D.

Charleston Radiation Therapy Consultants
THANK YOU

2009 AAPM SUMMER SCHOOL
CLINICAL DOSIMETRY MEASUREMENTS IN RADIOTHERAPY
JUNE 21-25, 2009 • COLORADO COLLEGE

Colorado Springs

PROGRAM DIRECTORS
David W.O. Rogers, Ph.D.
Joanna Cygler, Ph.D.

AAPM & SS SubCom
Local Arrangements Committee
Ms. Betsy Phelps-Medical Physics Publishing
Participants
OUTLINE

- Objectives
- Current calibration protocols
- E-beam quality specification
- Measurement of CA %DDs in water:
  - ion chambers, diodes, film
  - practical rules
- Output factors
- Non-water phantoms: Relative measurements
  - ion chambers, %DDs, film
- Small and irregular field dosimetry
- Extended treatment distances
- Electron algorithms
- Some data and examples
Objectives

- Address the issues that currently influence the dosimetry of clinical electron beams due to changes recently introduced by the new dosimetry calibration protocol (TG-51).
- Suggest how to appropriately modify and update the widely accepted TG-25 electron dosimetry protocol.
- Describe a detail procedure of converting measured depth-ionization curves with ion chambers into depth-dose curves making use of recently published stopping-power ratios and other conversion factors.
- Present the important points of the upcoming AAPM TG-70. *(Gerbi et al. Med. Phys. July 2009, issue!)*
Recommendations for clinical electron beam dosimetry: Supplement to the recommendations of Task Group 25

Bruce J. Gerbi
University of Minnesota, Minneapolis, Minnesota 55455

John A. Antolak
Mayo Clinic, Rochester, Minnesota 55905

F. Christopher Deibel
Cleveland Clinic, Cleveland, Ohio 44195

David S. Followill
The University of Texas M. D. Anderson Cancer Center, Houston, Texas 77030

Michael G. Herman
Mayo Clinic, Rochester, Minnesota 55905

Patrick D. Higgins
University of Minnesota, Minneapolis, Minnesota 55455

M. Saiful Hug
University of Pittsburgh Cancer Institute, Pittsburgh, Pennsylvania 15232

Dimitrio N. Mihailidio
Charleston Radiation Therapy Consultants, Charleston, West Virginia 25304

Ellen D. Yorke
Memorial Sloan-Kettering Cancer Center, New York, New York 10021

Consultants:
Kenneth R. Hogstrom
Louisiana State University, Baton Rouge, Louisiana 70803-4001

Faiz M. Khan
University of Minnesota, Minneapolis, Minnesota 55455

(Received 13 October 2008; revised 17 March 2009; accepted for publication 1 April 2009; published 18 June 2009)
Objectives

- Describe the use of water equivalent phantoms to perform relative electron dosimetry based on recently published conversions factors.
- Discuss small and irregularly shaped electron field dosimetry using the concept of lateral buildup ratio (LBR) as an avenue to evaluate electronic equilibrium and compute dose per MU for those fields.
- Give some common clinical examples where electron beam dosimetry is applied.
Important reports to have

- **TG-25** (Clinical electron beam dosimetry).
- **TG-51** (protocol for clinical dosimetry for high-energy photon and electron beams).
- **TG-69** (Radiographic Films for MV Beam Dosimetry).
- **TG-39** (The calibration and use of plane-parallel ionization chambers for dosimetry of electron beams).
- **TG-53** (Quality assurance for clinical radiotherapy treatment planning).
- **TG-106** (Accelerator beam data commissioning and procedures).
- **TG-70** (just published)
Current calibration protocols
Current calibration protocols

- **TG-51 of AAPM (1999).**
  - "Absorbed Dose determination in External Beam Radiotherapy: An International Code of Practice based on Standards of Absorbed Dose to Water"

- **TRS-398 of IAEA (2003).**
  - "Code of practice for electron dosimetry of radiotherapy beams with initial energy from 2 to 50 MeV based on air-kerma calibration"

- **Code of practice of IPEM (2006).**
Main objectives of TG-51

- Defines **Dose** at one point, $d_{\text{ref}}$.
- Proposes to do two things:
  1. Incorporate the new absorbed dose standard
     - Absorbed dose is more robust than the Air-Kerma Std.
     $$N^Q_{D,w} = k_q N^{60\text{Co}}_{D,w}$$
     - Dose to water is closer to the dose to tissue
  2. Simplify the calibration formalism (as much as possible)
- Makes use of **realistic** water-to-air restricted SPRs.
Because of TG-51 (and other recent dosimetry data), do we need to modify TG-25?

YES! TG-70 was charged!
E-Beam Quality Specification
Electron Beam Quality Specification

New beam quality specifier*: $R_{50}$ (depth in water at which dose falls to 50% of maximum for large field size (>10x10 cm$^2$) (TG-51).

- First find $I_{50}$ (50% of ionization maximum).

- $R_{50} = 1.029I_{50} - 0.06$ cm for $2 \leq I_{50} \leq 10$ cm

or

- $R_{50} = 1.059I_{50} - 0.37$ cm for $I_{50} \geq 10$ cm

*(TG-25, beam quality specifier: $(E_p)_0$)
Energy at depth

Harder’s Eq. still valid! (Harder 1968)

- Mean energy at depth:
  \[ \bar{E}_d = \bar{E}_0 \left( 1 - \frac{d}{R_p} \right) (MeV) \]

- Mean energy at surface of phantom: (IPEM 2003)
  \[ \bar{E}_0 = 0.656 + 2.059R_{50} + 0.022R_{50}^2 (MeV) \]
  or
  \[ \bar{E}_0 = 0.818 + 1.935I_{50} + 0.040I_{50}^2 (MeV) \]

- Practical range: (Rogers 1996)
  \[ R_p = 1.271R_{50} - 0.23(cm) \]
Energy at depth

Harder’s Eq. still valid! (Harder 1968)

Mean energy at depth:

\[
\bar{E}_d = \bar{E}_0 \left( 1 - \frac{d}{R_p} \right) (\text{MeV})
\]
Energy at surface and practical range

Mean energy at surface of phantom: *(IPEM 2003)*

\[
\bar{E}_0 = 0.656 + 2.059 R_{50} + 0.022 R_{50}^2 \text{(MeV)}
\]

or

\[
\bar{E}_0 = 0.818 + 1.935 I_{50} + 0.040 I_{50}^2 \text{(MeV)}
\]

Practical range: *(Rogers 1996)*

\[
R_p = 1.271 R_{50} - 0.23 \text{(cm)}
\]
Comment

Harder’s Eq. still valid!

- Mean energy at depth:
  \[ E_d = E_0 \left( 1 - \frac{d}{R_p} \right) \text{(MeV)} \]

- Use of (as of TG-25):

  \[ E_0 = 2.33 R_{50} \text{(MeV)} \]

  or

  \[ E_0 = 2.40 R_{50} \text{(MeV)} \]

Task Group 25 recommends that either the AAPM (1983) protocol value for \( C_i \) of 2.33 or the HPA (1985) protocol value of 2.4 times either the depth of 50% ionization or 50% dose, corrected or uncorrected for divergence, are acceptable for estimating the incident mean energy to be used for the calculation of relative dose. This task group recommends that, within this framework, the physicist select the method consistent with his or her calibration protocol.
Measurements of %DDs
Phantoms and detectors

- **WATER** for relative measurements (%DDs, OFs, etc) such as large data collection.
- **Plastic (non-Water)** for limited relative measurements of clinical setups (%DDs, OF, etc).
- **Detectors** (cylindrical, p-p, diodes, film)
Cylindrical chambers in water
Step 1: Shift chamber deeper by $0.5r_{cav}$
Step 2: Correct reading for $P_{ion}$, $P_{pol}$

$$M(d) = M_{raw}(d) \cdot P_{ion}(d) \cdot P_{pol}(d)$$

- Apply TG-51 requirements for $P_{ion}$ and $P_{pol}$
  (For %DD: measure at $I_{50}$ and $R_p$ depths)

$$\%di(d) = 100 \frac{M(d)}{M(I_{max})}$$
**Step 3: Use realistic SPRs water/air**

For Burns 1996 (in water)

\[
\left( \frac{\bar{L}}{\rho} \right)^w_{\text{air}} (R_{50}, z) = \frac{a + b(\ln R_{50}) + c(\ln R_{50})^2 + d\left(\frac{z}{R_{50}}\right)}{1 + e(\ln R_{50}) + f(\ln R_{50})^2 + g(\ln R_{50})^3 + h\left(\frac{z}{R_{50}}\right)}
\]

Where:

- \(a = 1.0752\)
- \(b = -0.50867\)
- \(c = 0.08867\)
- \(d = -0.08402\)
- \(e = -0.42806\)
- \(f = 0.064627\)
- \(g = 0.003085\)
- \(h = -0.12460\)

These coefficients give an rms deviation of 0.4% and a max. deviation of 1.0% for \(z/R_{50}\) between 0.02 and 1.1. The max. deviation increases to 1.7% if \(z/R_{50}\) values up to 1.2 are considered.
### Step 4

**a) Computation of \( \%DD \)**

**b) Correct for \( P_{fl} \) and \( P_{wall} \)**

\[
\%dd_{w}(d) = \%id_{w}(d) \times \frac{\left( \frac{L}{\rho} \right)^{w} (R_{50}, d) \cdot P_{fl}(\bar{E}_{d}) \cdot P_{wall}(d)}{\left( \frac{L}{\rho} \right)_{air}^{w} (R_{50}, d_{max}) \cdot P_{fl}(\bar{E}_{d_{max}}) \cdot P_{wall}(d_{max})}
\]
Errors associated with SPRs

Fitted SPRs vs. individually calculated

Error:
% of Max dose = % error of the fitted SPRs vs. individually calculated values.

Rogers has shown that the %DD can be determined to within 1% of the dose at $d_{\text{max}}$. (Rogers 2004)
Reminder: For electrons

\[ P_{\text{repl}} = P_{\text{gr}} \times P_{\text{fl}} \]

- \( P_{\text{gr}} \): addressed with chamber shift
- \( P_{\text{fl}} \): Use Table V in TG-25
$P_{fl}$ from TG-25

<table>
<thead>
<tr>
<th>$E_d$ (MeV)</th>
<th>Inner diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3</strong></td>
<td>0.977   0.962   0.956   0.949</td>
</tr>
<tr>
<td><strong>5</strong></td>
<td>0.978   0.966   0.959   0.952</td>
</tr>
<tr>
<td><strong>6</strong></td>
<td>0.982   0.971   0.965   0.960</td>
</tr>
<tr>
<td><strong>10</strong></td>
<td>0.985   0.977   0.972   0.967</td>
</tr>
<tr>
<td><strong>15</strong></td>
<td>0.992   0.981   0.978   0.978</td>
</tr>
<tr>
<td><strong>20</strong></td>
<td>0.997   0.996   0.995   0.995</td>
</tr>
</tbody>
</table>

*where $E_d = E_0(1 - d/R_p)$*
$P_{wall}$

$P_{wall} = 1$: for electron beams and low-Z thin-walled chambers (Johansson 1978)

$P_{wall}$: Recent data (Buckley & Rogers 2006) show change up to 2.5% at 0.5 cm-$R_{50}$ for 6 MeV.

**Recommendation**: make sure your chamber introduces less than 2% error at depths by comparing its response to published data.
p-p chambers in water
Use of p-p chambers for %DD

• In general, front of window is point of measurement
  Front window thickness (1-2mm) should be taken into account.
  $P_{gr}=0$ for all p-p chambers.
  $P_{fl}=1$ for most chambers except Markus and Capintec PS-033 (use TG-39 for correction factors).
  $P_{wall}$ corrections are considered negligible in most cases.

$P_{wall}$:
Recent data (Buckley & Rogers 2006) have shown strong depth dependence for NACP-02, Roos, Markus and Capintec PS-033.
Buckley&Rogers: p-p chambers

**Recommendation:**
Compare your chamber’s response with data from literature to be <2%

**Fig. 4.** $P_{\text{wall}}$ as a function of depth of measurement for an NACP chamber in a water phantom. The calculations were performed using the CSnrc user-code for nominal beam energies of 6 MeV and 20 MeV. The reference depths for each beam, $d_{\text{ref}}$, specified by the standard dosimetry protocols, are indicated by the arrows.
diodes in water
Use of diodes for \%DD

Diodes specifically designed for electron beams.

The effective point of measurement is the dye (get specs from manufacturer).

Validate \%DDs measured with diodes against curves measured with chambers (TG-25).

Have a QC program for diodes before taking large amount of data.
Use of diodes for %DD

1) Look at new TG-106  (Das 2008)

2) Look at this Summer School’s chapter
QUESTION
In an open field, a bull mistakenly eats an explosive device. What word best describes this situation?

1. Ridiculous
2. Frightening
3. Horrific
4. Abominable
5. Hungry

ABOMINABLE (A-Bomb-In-A-Bull)

Courtesy of J. Gibbons, PhD
General Characteristics of E-%DDs
definitions....

Therapeutic Range

Practical Range

ICRU 35 (1984)
As Energy increases

- Surface dose (at 0.5mm) ↑.
- $d_{\text{max}}$ ↑ for lower Es and stops at moderate/high Es.
- Beam penetration ($d_{90}$, $d_{50}$ and $R_p$) ↑.
- Distance between $d_{90}$-$d_{10}$ ↑.
- X-ray contamination ↑.
As beam energy increases....

Hogstrom (2003)
As field size decreases

- Surface dose (at 0.5mm) ↑.
- $d_{\text{max}}$ and $d_{90}$ ↓ (shift to surface).
- Distance between $d_{90}$-$d_{10}$ ↑.
- $R_p$ unchanged.
As field size decreases...

9 MeV

20 MeV

Hogstrom (2003)
Output factors
Definition

\[ S_e \left( d_{\text{max}} \left( r_a \right), r_a, SSD \right) = \frac{\dot{D}(d_{\text{max}} \left( r_a \right), r_a, SSD_{\text{treat}})}{\dot{D}(d_{\text{max}} \left( r_0 \right), r_0, SSD_{\text{nom}})} \]

- \( r_a \): treatment field at \( SSD_{\text{treat}} \)
- \( r_0 \): reference / cal field at \( SSD_{\text{nom}} \)
Non-water phantoms
Relative measurements
Use of non-water phantoms

- Water substitutes should mimic water across the whole electron energy range
  - mainly in stopping and scattering powers
    - thus, both the electron density and the effective atomic number should be matched to water
    - in practice for some phantoms, this is difficult to achieve (due to the carbon in plastics)
- off-the-shelf material can have large variations in density and scattering power
  - Must be careful in using these materials

SO:
USE WATER WHENEVER POSSIBLE!
Use of non-water phantoms discussion of corrections

- Depths need to be scaled.
- Chamber readings need to be multiplied by an appropriate fluence-ratio correction.
- Stopping-power ratios should be taken at the scaled depth.
- Charge storage effects should be kept in mind using polystyrene and PMMA.
**Corrections needed**

**Depth correction:**

\[ d_w = d_{med} \rho_{eff} = d_{med} \left( \frac{R_{50}^w}{R_{50}^{med}} \right) \]

**Corrected dose (Ding 1997):**

\[ D_w (d_w^{max}) = D_{med} (d_{med}^{max}) \left[ \left( \frac{L}{\rho} \right)_{coll} \right]_{med}^w \phi_{med}^w \]

Electron fluence correction factor
## Depth correction factors

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass density</th>
<th>Recommended effective density, $\rho_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water*</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Clear polystyrene*</td>
<td>1.045</td>
<td>0.975</td>
</tr>
<tr>
<td>High-impact polystyrene (white)*</td>
<td>1.055</td>
<td>0.99</td>
</tr>
<tr>
<td>Electron solid water*</td>
<td>1.04</td>
<td>1.00</td>
</tr>
<tr>
<td>Polymethylmethacrylate (PMMA)*</td>
<td>1.18</td>
<td>1.115</td>
</tr>
<tr>
<td>Epoxy resin water substitute, photon formulation**</td>
<td>1.02</td>
<td>0.98</td>
</tr>
</tbody>
</table>

*from TG-25, Table VII, p. 84.
**From IPEM 2003, p. 2945.
Output in non-water phantom

\[
S_{e,w}(d_{w}^{\text{max}}, r) = S_{e,\text{med}}(d_{\text{med}}^{\text{max}}, r) \cdot \frac{\left[ \phi(d_{\text{med}}^{\text{max}}, r) \right]_{\text{med}}^w}{\left[ \phi(d_{\text{med}}^{\text{max}}, r_0) \right]_{\text{med}}^w}
\]

\[\phi_{\text{med}}^w\] : Use data from Ding 1997.

NOTE: Since corrections appear as RATIOS might be negligible. CHECK it!
Measurements PDDs in non-water Phantoms

- The SSD and field size are not to be scaled.
- Chamber must be positioned with its effective point of measurement at the equivalent-scaled depth in the non-water phantom.
- Correct for electron fluence $\phi_{med}^w$
PDDs in non-water phantoms

- Cylindrical chambers

\[
\%dd_w(d^w) = \%di_{med}(d^{med}) \times \left( \frac{L}{\rho} \right)_\text{air}^w \frac{(R_{50}^w, d^w)}{(R_{50}^w, d_{\text{max}}^w)} \cdot P_{fl}(E_{d^{med}}) \times \frac{\phi_{med}(d^{med})}{\phi_{med}(d_{\text{max}}^{med})}
\]

- p-p chambers: \( P_{fl}=1 \)

- Film XV-2 (TG-25)

Large energy dependence
Dosimetry of small and irregular fields
Inherent problems in dosimetry of small electron fields

- depth of $d_{max}$ becomes shallower.
- the output factor may be significantly different than the cone factor if the field size is small enough for lateral scatter equilibrium (LSE).
- isodose coverage is reduced in all directions as the field shrinks.
Square-Root Method

For rectangular fields of X & Y dimensions:

\[
%dd(d, r_{X,Y}) = \left[\%dd(d, r_{X,X}) \times %dd(d, r_{Y,Y})\right]^{1/2}
\]

\[
S_e(d_m, r_{X,Y}) = \left[S_e(d_m, r_{X,X}) \times S_e(d_m, r_{Y,Y})\right]^{1/2}
\]

Approximate irregular shapes with rectangles

Hogstrom (2000)
Comparison of the percent difference between measured and calculated output factors for common methods of calculation in the literature. The measured and calculated output factors were for cutout shields that were shaped as squares, rectangles, circles, ellipses, and arbitrary shapes used in the clinic.

<table>
<thead>
<tr>
<th>Calculation method</th>
<th>Percent difference (≤±%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent square</td>
<td>2.7*, 5.9*, 3.0*</td>
</tr>
<tr>
<td>Square root</td>
<td>3.0*, 2.3*, 4.6*, 3.0*</td>
</tr>
<tr>
<td>One-dimensional</td>
<td>3.0*, 2.0*, 2.1*</td>
</tr>
<tr>
<td>Pencil beam</td>
<td>2.7*, 2.0*</td>
</tr>
<tr>
<td>Sector integration</td>
<td>3.0, 1.5, 1.0*</td>
</tr>
</tbody>
</table>

*(Jursinic 1997)*
Lateral Buildup Ratios (LBRs) Model

(Khan et al. 1999)
THE WRATH OF KHAN
When is special dosimetry required?

- When the minimum field dimension is less than the minimum radius of a circular field that produces lateral scatter equilibrium (LSE)

\[
R_{eq} = 0.88 \sqrt{E_{p,0}}
\]

or

\[
a \approx 1.58 \sqrt{E_{p,0}} \quad (Khan&Higgins 1999)
\]

where

\[
E_{p,0} = 0.22 + 1.98 R_p + 0.0025 R_p^2
\]
Do you remember what it has been?

- From *Lax&Brahme (1980)* we have been using the criterion for LSE:

\[
R_{eq} \approx \frac{E_0}{2.5}
\]

where

\[
E_0 = \overline{E}_0
\]

or

\[
E_0 = E_{p,0}
\]

(also in Khan’s book)
Pencil beam...

Due to multiple Coulomb Scattering

Khan et al. (1998)

\[ d_p(r, z) = D_\infty(0, z) \cdot \frac{\exp\left(-\frac{r^2}{\sigma_r^2(z)}\right)}{\pi \sigma_r^2(z)} \]
LBR definition

LBRs are related to $\sigma_r^2(d)$ mean square radial spread of pencil beam (independent of field size).

**DEFINITION of LBR:**

$$LBR(d,r) = \frac{D(d,r_x)}{D(d,r_\infty)} \cdot \frac{\Phi_i(r_\infty,E)}{\Phi_i(r,E)}$$

- $r_x$: small field (e.g., 2 cm radius)
- $r_\infty$: broad field (e.g., 20x20 cm$^2$)
- $\Phi(...)$: incident fluence (normalize at 0.5 mm depth)

*(Khan et al. 1998)*
Measured PDDs normalized at 0.5 mm depth (surface)

Khan et al. (1998)
Determine

- Take a small circular field $r_x = 2$ cm diam. to measure PDDs and ratio those to PDDs from a 20x20 cm$^2$, normalized both at 0.5 mm, to determine LBRs.

\[
\sigma_r^2(d) = \frac{r_x^2}{\ln \left[ \frac{1}{1 - LBR(r_x, d)} \right]}
\]

with $LBR < 1$

(Khan et al. 1998)
Sigma vs. field size and energy

Sigma vs. field size and energy

Figure 3. A plot of $\sigma_r$ as a function of $z/R_p$, for $\sigma_r$ values extracted from LBR data for field sizes of 2, 2.8 and 3.7 cm diameter and beam energy of 9 MeV.

Khan et al. (1998)
In which applicator to use the $r_x$ field?

It does NOT matter!

2 cm diam. insert in 10x6, 10x10 and 20x20 cm$^2$ applicators
For irregularly shaped fields…

- Sector integration summing the pencil beam contributions.

\[ LBR_{\text{eff}}(d, r) = 1 - \left( \frac{\Delta \theta}{2\pi} \right) \sum_{i=1}^{n} \exp \left[ -\frac{r_i^2}{\sigma_r^2(d)} \right] \]
Can we predict $d_{\text{max}}$ for small fields?

- Circular fields as example, within $\pm 0.5\%$ of maximum dose.

\[
d_{\text{max}}^{r_x} \approx \left(0.174 r_x^{0.67} E_{p,0}^{1.67} - 0.0625 E_{p,0}^2\right)^{0.33}
\]

\[
d_{\text{max}}^{R_{\text{eq}}} \approx 0.46 E_{p,0}^{0.67}
\]

$r_x \leq R_{\text{eq}}$

$r_x \geq R_{\text{eq}}$

For broad field

Relative applicator

Output Factor

$S_e(d, r_j) = S_e \times LBR_{\text{eff}}(d, r_j) \times \% dd_{\infty}(d, r_{\infty})$

(Khan & Higgins 1999)
Data vs. predictions for small circular fields

Table 1. Depths of maximum dose, $d_{max}$, for circular and rectangular fields. Calculated values are given by equation (7) for circular fields and by equation (8) for rectangular fields. $R_{eq}$ is given by equation (2).

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Field radius or size</th>
<th>$d_{max}$ measured $^\dagger$ (cm)</th>
<th>$d_{max}$ calculated (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 ($R_{eq} = 2.2$ cm)</td>
<td>1.0</td>
<td>0.9–1.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.1–1.3</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>1.3–1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3 × 3</td>
<td>1.3–1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3 × 5</td>
<td>1.4–1.5</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>$\geq R_{eq}$</td>
<td>1.4–1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>9 ($R_{eq} = 2.6$ cm)</td>
<td>1.0</td>
<td>1.0–1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.4–1.7</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>1.7–2.0</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>3 × 3</td>
<td>1.7–2.1</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>3 × 5</td>
<td>1.9–2.1</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>$\geq R_{eq}$</td>
<td>1.9–2.1</td>
<td>2.0</td>
</tr>
<tr>
<td>12 ($R_{eq} = 3.0$ cm)</td>
<td>1.0</td>
<td>1.0–1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.0–2.2</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>1.4–2.6</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>3 × 3</td>
<td>1.3–2.5</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>3 × 5</td>
<td>1.5–2.7</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>$\geq R_{eq}$</td>
<td>2.2–3.0</td>
<td>2.4</td>
</tr>
<tr>
<td>16 ($R_{eq} = 3.5$ cm)</td>
<td>1.0</td>
<td>0.7–1.5</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>1.3–2.0</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>1.5–2.7</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>3 × 3</td>
<td>1.5–2.7</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>3 × 5</td>
<td>1.5–2.7</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>$\geq R_{eq}$</td>
<td>2.0–3.2</td>
<td>2.9</td>
</tr>
<tr>
<td>20 ($R_{eq} = 3.9$ cm)</td>
<td>1.0</td>
<td>0.8–1.5</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>0.8–2.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>1.9</td>
<td>1.0–2.7</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>3 × 3</td>
<td>1.0–2.7</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>3 × 5</td>
<td>1.0–2.8</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>$\geq R_{eq}$</td>
<td>1.0–3.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

$^\dagger$ Range of depths within ±0.5% of maximum dose.
Data vs. predictions for small circular fields

Table V. Calculated vs. Measured dose per monitor unit for rectangular fields using equivalent radius method.

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Field Size (cm²)</th>
<th>Diameter (cm)</th>
<th>Depth (cm)</th>
<th>Dose/MU (cGy/MU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>z100</td>
<td>z90</td>
</tr>
<tr>
<td>9</td>
<td>3x3</td>
<td>3.4</td>
<td>2.0</td>
<td>2.6</td>
</tr>
<tr>
<td>3x5</td>
<td></td>
<td>4.0</td>
<td>2.2</td>
<td>2.8</td>
</tr>
<tr>
<td>4x4</td>
<td></td>
<td>4.4</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>4x10</td>
<td></td>
<td>5.0</td>
<td>2.3</td>
<td>2.9</td>
</tr>
<tr>
<td>16</td>
<td>3x3</td>
<td>3.4</td>
<td>2.0</td>
<td>3.9</td>
</tr>
<tr>
<td>3x5</td>
<td></td>
<td>4.0</td>
<td>2.5</td>
<td>4.2</td>
</tr>
<tr>
<td>4x4</td>
<td></td>
<td>4.4</td>
<td>2.7</td>
<td>4.4</td>
</tr>
<tr>
<td>4x10</td>
<td></td>
<td>5.4</td>
<td>3.0</td>
<td>4.7</td>
</tr>
</tbody>
</table>

a. Equivalent diameter calculated by Eq. 12 and Eq. 9.
b. Calculated by Eq. 2; LBR was determined for the equivalent radius by using Eq. 6 and Eq. 8.

(Khan et al. 1998)
Treatments at extended distances
Electron beam features at extended SSDs

- Differences in PDDs resulting from InvSq. effect are small because electrons do not penetrate that deep and because the significant increase of penumbra width with SSD restricts the SSD to 115 cm or less in clinical practice (Hogstrom 2003).

- The depth of $d_{\text{max}}$ at extended SSD is a complex function of field size and beam energy. For small field sizes, the $d_{\text{max}}$ depth changes little. As the field size increases (>10x10 cm$^2$), the $d_{\text{max}}$ depth increases very slowly for electron energies below 12 MeV. For higher energies, the $d_{\text{max}}$ depth increases with increasing SSD (Das et al. 1995, Cygler et al. 1997).

- However, this effect is clinically insignificant since higher electron energies have broad $d_{\text{max}}$ ranges. In addition, beam flatness decreases and penumbra width increases at extended SSD, an effect more pronounced at smaller field sizes and lower electron energies. (also in Khan’s book)
Treatment planning systems (without Monte Carlo) differ in their ability to accurately depict the effects of extended SSD and individual institutions should investigate the limitations of their planning systems before use on patients.

Use TG-25 recommendations.
Beam output at extended distances

The Effective-SSD (SSD$_{\text{eff}}$) method
How to determine $SSD_{eff}$

- For every applicator and energy plot:

\[
g = SSD_{ext} - SSD_{nom}
\]

$I_o$: Rdg at $SSD_{nom}$

$I$: Rdg at $SSD_{ext}$

$SSD_{ext}$: extended SSD (typically <115 cm)

$SSD_{nom}$: 100 cm

(TG-25 & in Khan’s book)
## Data from Siemens Primus

### 7 MeV

<table>
<thead>
<tr>
<th>CONE</th>
<th>INSERT</th>
<th>$d_{\text{max}}$</th>
<th>S</th>
<th>SSD$_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIZE</td>
<td>SIZE</td>
<td>[cm]</td>
<td>[cm]</td>
<td></td>
</tr>
<tr>
<td>10x10</td>
<td>2x2</td>
<td>0.9</td>
<td>0.791</td>
<td>33.1</td>
</tr>
<tr>
<td>&quot;</td>
<td>3x3</td>
<td>1.2</td>
<td>0.870</td>
<td>46.6</td>
</tr>
<tr>
<td>&quot;</td>
<td>4x4</td>
<td>1.4</td>
<td>0.957</td>
<td>55.4</td>
</tr>
<tr>
<td>&quot;</td>
<td>6x6</td>
<td>1.4</td>
<td>1.001</td>
<td>61.5</td>
</tr>
<tr>
<td>&quot;</td>
<td>8x8</td>
<td>1.6</td>
<td>0.998</td>
<td>73.6</td>
</tr>
<tr>
<td>5cm</td>
<td>5cm</td>
<td>1.5</td>
<td>0.817</td>
<td>57.3</td>
</tr>
<tr>
<td>10x10</td>
<td>10x10</td>
<td>1.6</td>
<td>1.000</td>
<td>83.9</td>
</tr>
<tr>
<td>15x15</td>
<td>15x15</td>
<td>1.6</td>
<td>0.998</td>
<td>99.4</td>
</tr>
<tr>
<td>20x20</td>
<td>20x20</td>
<td>1.6</td>
<td>1.001</td>
<td>100.4</td>
</tr>
<tr>
<td>25x25</td>
<td>25x25</td>
<td>1.6</td>
<td>0.992</td>
<td>106.0</td>
</tr>
</tbody>
</table>

### 14 MeV

<table>
<thead>
<tr>
<th>CONE</th>
<th>INSERT</th>
<th>$d_{\text{max}}$</th>
<th>S</th>
<th>SSD$_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIZE</td>
<td>SIZE</td>
<td>[cm]</td>
<td>[cm]</td>
<td></td>
</tr>
<tr>
<td>10x10</td>
<td>2x2</td>
<td>1.2</td>
<td>0.893</td>
<td>58.7</td>
</tr>
<tr>
<td>&quot;</td>
<td>3x3</td>
<td>1.6</td>
<td>0.918</td>
<td>66.4</td>
</tr>
<tr>
<td>&quot;</td>
<td>4x4</td>
<td>2.0</td>
<td>0.944</td>
<td>62.5</td>
</tr>
<tr>
<td>&quot;</td>
<td>6x6</td>
<td>2.6</td>
<td>0.987</td>
<td>71.5</td>
</tr>
<tr>
<td>&quot;</td>
<td>8x8</td>
<td>2.9</td>
<td>0.995</td>
<td>79.1</td>
</tr>
<tr>
<td>5cm</td>
<td>5cm</td>
<td>2.7</td>
<td>0.922</td>
<td>82.0</td>
</tr>
<tr>
<td>10x10</td>
<td>10x10</td>
<td>2.9</td>
<td>1.000</td>
<td>94.2</td>
</tr>
<tr>
<td>15x15</td>
<td>15x15</td>
<td>2.9</td>
<td>0.984</td>
<td>103.5</td>
</tr>
<tr>
<td>20x20</td>
<td>20x20</td>
<td>2.9</td>
<td>0.957</td>
<td>104.6</td>
</tr>
<tr>
<td>25x25</td>
<td>25x25</td>
<td>2.9</td>
<td>0.957</td>
<td>106.9</td>
</tr>
</tbody>
</table>

(Mihailidis, et al.)
### Weak dependence of $SSD_{eff}$ on applicator size (Varian 2100 Data)

| Aperture size (cm$^2$) | Inert size (cm$^2$) | Energy (MeV) | | | |
|------------------------|---------------------|--------------|---|---|---|---|---|
|                        |                     | 6  | 9  | 12 | 16 | 20 |
| 10×10                  | 4×4                 | 44.1| 60.1| 72.8| 76.6| 74.3|
|                        | 6×6                 | 62.5| 74.6| 80.2| 81.8| 78.4|
|                        | 8×8                 | 77.7| 82.8| 83.5| 85.7| 83.0|
|                        | 10×10               | 83.6| 88.3| 89.1| 87.5| 84.8|
| 20×20                  | 4×4                 | 44.9| 61.3| 72.9| 75.9| 77.8|
|                        | 6×6                 | 62.1| 74.1| 79.4| 81.8| 82.1|
|                        | 8×8                 | 78.6| 82.2| 82.0| 81.4| 82.4|
|                        | 10×10               | 83.7| 84.7| 86.5| 84.1| 83.4|
|                        | 15×15               | 90.6| 90.1| 89.8| 89.2| 89.8|
|                        | 20×20               | 90.6| 91.5| 91.8| 91.9| 92.9|
| 25×25                  | 4×4                 | 49.5| 61.9| 71.8| 76.6| 77.8|
|                        | 6×6                 | 63.3| 75.5| 81.1| 81.8| 81.3|
|                        | 8×8                 | 76.6| 86.3| 84.2| 83.7| 82.7|
|                        | 10×10               | 81.4| 84.8| 84.8| 85.0| 83.3|
|                        | 15×15               | 90.7| 91.6| 90.3| 90.8| 89.6|
|                        | 20×20               | 89.3| 92.1| 91.0| 89.9| 91.1|
|                        | 25×25               | 90.7| 91.9| 91.0| 92.5| 93.3|

<table>
<thead>
<tr>
<th>Insert size (cm$^2$)</th>
<th>Beam Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>6.1</td>
</tr>
<tr>
<td>6</td>
<td>62.2</td>
</tr>
<tr>
<td>8</td>
<td>77.6</td>
</tr>
<tr>
<td>10</td>
<td>82.9</td>
</tr>
<tr>
<td>15</td>
<td>90.7</td>
</tr>
<tr>
<td>20</td>
<td>90.0</td>
</tr>
<tr>
<td>25</td>
<td>90.7</td>
</tr>
</tbody>
</table>

Averaged data (Roback et al. 1995)
Output at extended distances

\[ S_e(d_m, SSD_{ext}) = S_e(d_m, SSD_{nom}) \times GF \]

with

\[ GF = \left( \frac{SSD_{eff} + d_{\text{max}}}{SSD_{eff} + d_{\text{max}} + g} \right)^2 \]

Monitor Units:

\[ MU = \frac{D_{\text{prescription}}}{S_e(d_m, SSD_{ext})} \]

(Khan et al. 1998)
QUESTION
The bomb exploded. What word best describes this situation?

1. Sad
2. Disgusting
3. Noble
4. Horrific
5. Silly

NOBLE (No-Bull)
Electron Beam Algorithms
(Simple discussion)
General Comments

- What should be done to commission these algorithms (being consistent with TG53)
  - know the pitfalls and limitations of electron algorithms
  - careful with normalization of dose distributions for electron algorithms
    - Restricted field
    - Extended treatment distance
    - Plans involving inhomogeneities
- Attention to how data should be entered into the program.
Some clinically relevant tests

- Inhomogeneities in electron treatments
  - The effects of inhomogeneities on dose distributions
  - Computer representation of the effects of dose inhomogeneities
- Use of bolus
- Field abutment
  - Electron-electron, with same or different energies
  - Electron-photon, with standard or extended distances
  - Tertiary shielding for field abutment
- Library of clinical treatment examples
Acknowledgment

- Members of TG-70 group.
- Faiz Khan.
- Dave Rogers.
- Ken Hogstrom.
- Bruce Gerbi (Chair of TG-70).
Not done yet
Stay where you are!
Problem

A small area will be treated with 16 MeV electrons and a custom circular field of 5.5 cm diameter (average), at 100 SSD. What are the necessary dosimetric parameters to be measured in order to determine the output of such field?
1. See if there is LSE:
   In practice: $R_p = \frac{16\text{MeV}}{2} = 8\text{ cm}$

   $E_{p_0} = 16.2\text{MeV}$, then: $R_{eq} = 0.88\sqrt{16.2} = 3.5\text{ cm}$ radius

   Thus: NO LSE $\Rightarrow d_{max}$ would be shifted towards surface.

2. Find new $d_{max}$ for the 5.5 cm diam field with:
   a) Film dosimetry - film parallel to beam in solid water.
   b) Ion chamber in solid water and thin sheets of 1 mm thickness

   To estimate the new $d_{max}$:
   $$d_{max} = (5.5\text{cm}) = (0.174 \times E_{p_0} - 0.0625E_{p_0}^2)$$

   $d_{max} = 2.8\text{ cm}$ instead of $d_{max} = 3.4\text{ cm}$ for 10x10 field.
3) Measure output factor of 5.5 cm field @ new dmax relative to 10x10 @ 3.4 cm depth, both at 100 SSD.

4) From film or p-chamber measurements find d_{90, dso} and at those depths measure isodose lines with film perpendicular to beam. Scan films cross/ in plane to find the width of 95\%, 90\%, 80\%, & 50\% isodose lines @ d_{max}, d_{90}, d_{80} depths.
Solution

- Check for LSE first. In practice cm and $E_{p,0}=16.2$ MeV (from (12.19)). Then, $R_{eq}=3.5$ cm (eq. (12.18)), thus no LSE since a diam=7 cm will be required.

- Need to find new $d_{\text{max}}$ that is shifted towards the surface. Use either film dosimetry with film placed parallel to electron beam in solid water or plane-parallel chamber in solid water with thin sheets of 1 mm to measure the $d_{\text{max}}$. An estimate of expected $d_{\text{max}}$ for the 5.5 cm diam. field is: 2.8 cm (from (12.24)).

- Measure the output factor of 5.5 cm field at 2.8 cm (new $d_{\text{max}}$) relative to the reference 10x10 at 3.4 cm, both at 100 SSD.

- From film or plane-parallel chamber dosimetry find $d_{\text{max}}, d_{90}, d_{80}$ and at those depths measure isodose lines with film perpendicular to beam in solid water. Scan films in-plane and cross-plane to get the widths of 95%, 90%, 80% and 50% isodose lines at the above depths.
THANK YOU!

Now, let’s go for a brew or two!